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(54) LASER ILLUMINATION WITH SPECKLE REDUCTION

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(58) Field of Search 359/495, 496; 372/9, 26, 98

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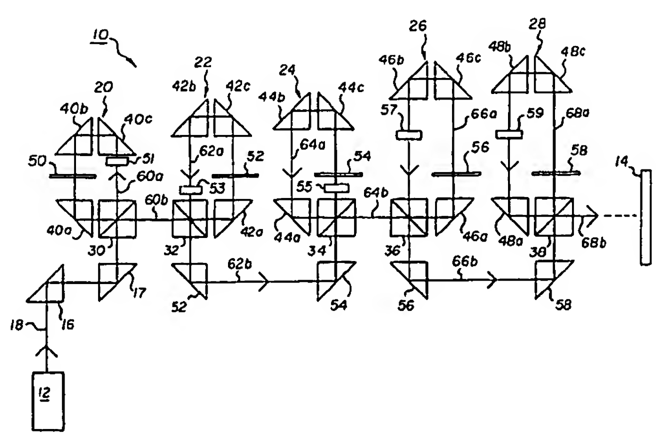
(57) ABSTRACT

A speckle reduction system divides pulses of coherent radiation into successions of temporally separated and spatially aberrated pulselets. One or more beamsplitters divide the pulses into the successions of pulselets that are circulated through delay lines. Spatial aberrators located along the delay lines modify wavefront shapes of the pulselets. Together, the temporal separation and spatial aberration of the pulselets produce a succession of different speckle patterns that can be averaged together within the integration interval of a detector to reduce speckle contrast.

27 Claims, 3 Drawing Sheets



and aberrating plates **110** and **120**, **112** and **122**, **114** and **124**, and **116** and **126** are positioned along the linear delay lines **90**, **92**, **94**, and **96**, which terminate with full mirrors **130**, **132**, **134**, and **136**. The wave plate **100** directs pulselets emerging from delay line **90** through the beamsplitter **84** and into delay line **92** rather than back to the laser source **82**. The wave plate **102** directs pulselets from the delay line **92** through the beamsplitter **84** toward the beamsplitter **86**. The wave plates **104** and **106** perform similar functions first directing the pulselets from the third delay line **94** into the fourth delay line **96** and then from the fourth delay line **96** toward a detector **140**.

The reciprocating paths of the linear delay lines **90**, **92**, **94**, and **96** transmit the pulselets in two opposite directions through the aberrators **120**, **122**, **124**, and **126**. Accordingly, the magnitudes of the individual aberrations produced by the aberrators **120**, **122**, **124**, and **126** can be only one-half of the magnitudes of the wavefront variations that would otherwise be required for single directions of travel along the delay lines **90**, **92**, **94**, and **96**. Variations between aberrators **120**, **122**, **124**, and **126** within or between the linear delay lines **90**, **92**, **94**, and **96** are possible to further randomize wave forms of the individual pulselets or combinations of the pulselets within the coherence length "λ_C".

The optical path lengths of the linear delay lines **90**, **92**, **94**, and **96** and the spacing between the partial mirrors **110**, **112**, **114**, and **116**, as well as the spacing of the full mirrors **130**, **132**, **134**, and **136** are adjusted to optimize a number "N" of independent pulselets separated by more than the coherence length "λ_C". The composite length "L_T" of the temporally spaced pulselets that make up the extended pulse beam **98** is preferably matched to the integration interval of the detector **140**.

Although shown as straight lines, the linear delay lines **90**, **92**, **94**, and **96** could also be arranged with equivalent optical pathways that bend or even wrap around to save space. Alignment optics or frequency shifters could also be added to provide advantages similar to those of the preceding embodiment.

More or fewer delay lines can be used to generate a desired number of independent pulselets separated beyond the coherence length. In fact, a single delay line may be sufficient for some purposes. The number of beam dividers and the form of aberrators paired with each of the beam dividers within the delay lines can also be adjusted to affect both the number and the spatial aberration of the independent pulselets. Each of the paired beam dividers and aberrators could also be formed by a common optic that performs both functions.

The graphs of FIGS. **3** and **4** illustrate normalized pulse transmissions and numbers of pulselets distributed over a common domain of delay produced by a combination of eight recirculating delay lines similar to FIG. **1**. At shorter delays of less than 15 mm, the pulselets have relatively large but widely varying energy content. Few of the total number of pulselets are within this range. Most of the pulselets are distributed around a delay of approximately 24 mm. However, the energy content of the pulselets rapidly decays starting at slightly longer delays.

An even distribution of energy is preferred among the pulselet combinations that contribute independent speckle patterns. In fact, the contrast formula in terms of "N" speckle patterns makes this assumption. A lesser reduction in speckle contrast is expected if the average intensities of the independent speckle patterns vary too widely. The reflectivity of the beamsplitters can be adjusted to achieve a more even energy distribution. Furthermore, the reflectivity of the beamsplitters or partially reflective surfaces can be varied as a function of radial or lateral position in the pulselet fields to differentially reflect different cross-sectional areas of the pulselets.

A variety of other techniques can be used in combination with the delay and aberrating techniques to produce more independent pulselets within the limiting integration interval. For example, the pulselets can be shifted in polarization with respect to each other to effectively double the number of independent pulselets. A spectral disperser, **142** (see FIG. **2**) such as a prism or diffractive optic, positioned in advance of the beamsplitter **84** could also be used in conjunction with our illuminator to spatially spread different wavelengths within the spectral bandwidth. The spacing variation is preferably within the envelope of the otherwise spatially aberrated beam emerging from the illuminator. Rotating beam prisms (such as Dove prisms) can be located in the delay lines to produce different spatial distributions of the wavelengths. This provides a greater degree of independence for overlapping pulselets with a common delay (i.e., within the coherence length).

We claim:

1. A speckle reduction system for a coherent optical source comprising:
   - a beamsplitter that divides a pulse of coherent radiation into a series of pulselets having substantially common cross-sectional areas with the pulse;
   - a delay line that separates the series of pulselets into a succession of temporally spaced pulselets;
   - an aberrator that spatially distinguishes wavefront shapes of the pulselets within the succession of pulselets; and
   - the succession of aberrated pulselets being sufficiently temporally spaced and aberrated to produce a succession of different speckle patterns that accumulate incoherently over an interval for reducing speckle contrast.

2. The system of claim **1** in which the delay line returns pulselets to the beamsplitter so that some of the pulselets are further divided into additional temporally spaced pulselets.

3. The system of claim **1** in which the delay line temporally separates a plurality of the pulselets beyond a coherence length of the coherent radiation.

4. The system of claim **1** in which the beamsplitter is a first of a plurality of beamsplitters and the delay line is a first of a plurality of delay lines for further dividing the temporally spaced pulselets into additional temporally spaced pulselets.

5. The system of claim **4** in which the first beamsplitter divides the pulselets output from the first delay line between an input to the first delay line and an input to the second beamsplitter.

6. The system of claim **5** in which a second of the beamsplitters divides pulselets output from a second of the delay lines between an input to the second delay line and an input to a remaining part of the system.

7. The system of claim **6** in which the aberrator is a first of a plurality of aberrators, the first aberrator being located along the first delay line and a second of the aberrators being located along a second of the delay lines.

8. The system of claim **1** in which the delay line has a closed shape that recirculate further divisions of the pulselets in a common direction along the delay line.

9. The system of claim **1** in which the delay line has an open shape that reciprocates further divisions of the pulselets in opposite directions along the delay line.

10. The system of claim **9** further comprising additional beamsplitters located along the delay line to reciprocate the further divisions of the pulselets.

11. The system of claim 1 further comprising a frequency shifter positioned in the delay line to reduce an effective coherence length of the coherent radiation.

12. The system of claim 1 further comprising a spectral disperser positioned in advance of the beamsplitter for spatially separated different wavelengths of the coherent radiation.

13. The system of claim 1 further comprising a detector having an integration interval that approximately matches a combined length of the succession of aberrated pulses.

14. A method of reducing speckle contrast comprising the steps of:

dividing a pulse of coherent radiation into a series of pulselets having coaxial wavefronts;

temporally separating at least some of the pulselets beyond a coherence length of the radiation; and

spatially aberrating the coaxial wavefronts of the temporally separated pulselets with respect to each other so that the temporally separated pulselets produce different speckle patterns.

15. The method of claim 14 in which the step of dividing includes redividing at least some of the pulselets, the step of temporally separating includes temporally separating the redivided pulselets, and the step of spatially aberrating includes spatially aberrating the redivided pulselets to produce more of the different speckle patterns.

16. The method of claim 14 in which the steps of dividing and temporally separating the pulselets include circulating progressive divisions of the pulselets along a continuous path.

17. The method of claim 16 in which the pulselets are circulated along the continuous path in a single direction.

18. The method of claim 14 in which the steps of dividing and temporally separating the pulselets include reciprocating progressive divisions of the pulselets along a linear path.

19. The method of claim 18 in which the pulselets are reciprocated along the linear path in two opposite directions.

20. The method of claim 14 in which the temporally separated pulselets extend through a length to approximately fill an integration interval of a detector that records the speckle patterns.

21. A speckle reduction system of an illuminator comprising:

a source of substantially coherent radiation having a limited coherence length;

a beam divider that divides a pulse of the coherent radiation into a series of pulselets that are directed along optical pathways distinguished in optical length by at least the coherence length of the radiation;

a plurality of spatial aberrators that are located along the optical pathways and that change wavefront shapes of the pulselets directed along the optical pathways; and

a beam combiner that combines pulselets into a succession of overlapping pulses that are sufficiently temporally spaced and spatially aberrated to produce a corresponding succession of different speckle patterns.

22. The system of claim 21 in which the beam divider is a first of a plurality of beam dividers for further dividing the temporally spaced pulselets into additional temporally spaced pulselets.

23. The system of claim 21 in which the pulselets produced by the beam divider have substantially common cross-sectional areas with the pulse.

24. The system of claim 21 further comprising a delay line that returns pulselets to the beam divider so that some of the pulselets are further divided into additional temporally spaced pulselets.

25. The system of claim 21 in which at least some of the spatial aberrators located along the optical pathways differ from each other to further vary the succession of different speckle patterns.

26. The system of claim 25 in which the spatial aberrators differ in orientation.

27. The system of claim 25 in which the spatial aberrators differ in shape.

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